Fuzzy multi-objective decision model for facility location selection with partiality criteria

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The developments achieved in the field of location allocation models have not been outstandingly successful in use by decision makers in this regard. The obstacles that hinder a more widespread exploitation of mathematical results are twofold: the intrinsic difficulties of the relevant problems and the tradeoff to be balanced between the different objectives. Facility location site selection is a multi-objective decision problem. It has a mix of quantitative and qualitative objectives where in many cases decision-makers may prefer certain locations than others. The purpose of this work is to develop a practical fuzzy based multi-objective decision model that incorporates partiality information. It can be used in ranking candidate site for different facility location sites and hence enhance the process of site selection. The model applicability is demonstrated through utilizing a comprehensive hypothetical numerical example.

رغم التطورات التي طرأت على النماذج الرياضة المستخدمة فى اختيار مواقع أماكن انشاء التسهيلات و التى لها أثر واضح على العائد الاقتصادي لهذه المنشآت الا ان عدد قليل قد أمكن استخدامه بواسطة متخذي القرار فى اختيار المواقع للمنشآت والمؤسسات بنوعيها الصناعية و الخدمية. وترجع العقبات التى تعوق انتشار استخدام نتائج هذه النماذج الرياضية الى سببين رئيسين هما: الصعوبة الكامنة والمرتبطة بطبيعة تحديد اعتبارات الاختيار وثانيا صعوبة المفاضلة بين الأهداف المختلفة و التى تكون احيانا متعارضة. وتعتبر مشكلة اختيار مواقع أماكن التسهيلات فى المنشآت الصناعية و الخدمية مشكلة صناعة قرار متعدد الأهداف. حيث أنها تحتوى على العديد من الأهداف الكمية والنوعية والتى عادة ما يكون لمتخذي القرار دور فى تفضيل مكان عن الآخر. ويقدم هذا العمل نموذج هلامي متعدد الأهداف. ويشمل اعتبارات متعددة التفضيل. ويمكن ان يستخدم فى ترتيب بدائل الامكان المتاحة ومن ثم تحسين عملية اتخاذ القرار. هذا وقد اثبت النموذج قدرة عالية فى التطبيق وذلك عن طريق استخدامه فى مشكلة افتراضية لاختيار موقع.

Keywords: Multi-objective decision making, Facility location selection, Fuzzy decision making

1. Introduction

The concept of appropriate facility site selection ranks among the crucial decisions to be made by a wide range of private and public firms. This is due to the fact that the location decision is of strategic and long-term significance in that, once a commitment has been made in this respect, the choice is generally viewed as definitive and irreversible. For a majority of enterprises, facility location selection is an exceptional and unique event in which they lack experience and for which there are no well defined criteria to relay on [1]. Consequently, companies often depend on intuition and heuristic rules of thumb in selecting appropriate location.

Facility location selection decision models are closely related to location theory. The analysis of site location is surprisingly old. Most of the initial work was performed in Germany. In 1826, Johann H. von Thunen examined the optimal location for agricultural crops with respect to an industrialized city. The study of location theory formally began in 1909 when Alfred Weber considered how to position a single warehouse so as to minimize the total distance between it and several customers [2]. Following this initial investigation, location theory was driven by a few applications which inspired researchers from a range of fields.

Since the mid-1960s, the study of location theory has flourished. The most basic facility location problem formulations can be

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characterized as both static and deterministic [3]. These problems take constant, known quantities as inputs and derive a single solution to be implemented at one point in time. The solution is chosen according to one of many possible criteria (or objectives), as selected by the decision maker. A number of researchers, particularly those working with applied problems, have examined multi-objective extensions of these basic models [4].

Finding robust facility locations is thus a difficult task, demanding that decision-makers account for uncertain future events. The complexity of this problem has limited much of the facility location literature to simplified static and deterministic models. Although few researchers initiated the study of stochastic and dynamic aspects of facility location many years ago, most of the research dedicated to these issues has been published in recent years [5]. Dynamic formulations focus on the difficult timing issues involved in locating a facility (or facilities) over an extended horizon [6-8], where, stochastic formulations attempt to capture the uncertainty in problem input parameters such as forecast demand or distance values [9].

The objective of this paper, therefore, is to present a fuzzy multi-objective decision model capable of handling the facility location site selection problem. It also shows how preference information affects location allocation decision.

2. Facility location selection

Facility location has a well-developed theoretical background where, generally, optimizing methodologies were dominating [10,11]. Many methodologies have been utilized to solve the location-allocation problem including fundamental transportation assignment, and the linear programming formulation [12]. Integer and mixed integer formulations have been applied by many researchers [13].

Geoffrion's work [14], included decomposition, mixed integer linear programming, simulation and heuristics as solution paradigms that could be used in analyzing location problems. He noted that a suitable methodology for supporting managerial decision making for location problems should be computationally efficient, leading to optimal solution, and capable of further testing.

Other methodologies that have been employed include dynamic programming [15], multivariate statistics such as multidimensional scaling [16] and heuristic and search procedures [17,18,19]. Bowen [20], for example, used Monte-Carlo simulation and subjective evaluations to compare the Analytic Hierarchy Process (AHP) and probabilistic multidimensional scaling (PROSCAL) in the context of selecting the nuclear waste site.

Lee [21] considered the unreliability of facilities. He proposed efficient solution methods to determine locations for these facilities in the unreliable location model. While, Marsh and Schilling [22] addressed the equity measurement issue in facility location analysis, and introduced a framework and common notation for organizing them.

Although the simulated annealing paradigm inspired many for approximately solving combinatorial optimization problems, Righini [23] introduced a double-annealing algorithm, for the first time, for the application of annealing-based algorithms to discrete location/allocation problems, with two mutually dependent sets of binary variables.

Lee et al. [24] presented work on multiple criteria model for location allocation problem. Many years later, Maniezzo, et al. [25], applied multicriteria decision analysis for the best siting of plants, minimizing costs and environmental impacts, to the problem of locating installations for industrial waste management.

In many facility location problems, objectives such as cost minimization may not be the most important factor [1]. Qualitative objectives are crucial but often cumbersome and usually treated as part of management responsibility in analyzing results rather than quantified and included in a model formulation of the location-allocation problem [24, 26].

Although the above mentioned models utilized many mathematical models and techniques, they lack the consideration of: first, the evaluation of fuzzy information, second the partiality criteria (information) of certain locations. Thus, the main objective of this work is to develop a practical fuzzy based multi-objective decision model that incorporates partiality (preference) information. Hence, it will provide managers with a more effective and efficient model for making facility location site selection decisions.

3. Fuzzy set theory as decision-making tool

Application of fuzzy sets within the field of decision making has, for the most part, consisted of extensions or "fuzzifications" of the classical theories of decision making. While decision making under conditions of risk and uncertainty has been modeled by probabilistic decision theories and game theories, fuzzy decision theories attempt to deal with the vagueness or fuzziness inherent in subjective or imprecise determinations of preferences, constraints, and goals [27-30].

The process of assigning membership functions to fuzzy variables is either intuitive or based on some algorithmic or logical operations [31]. Intuition is simply derived from the capacity of experts to develop membership functions through their own intelligence and judgment.

The mathematical techniques for dealing with fuzziness are simpler in many ways than those of probability theory since in fuzzy set theory the simpler notion of membership function corresponds to the notion of probability measure in probability theory [32]. Nevertheless, one should note that since fuzzy models yield only best and worst case analysis and do not assume that errors compensate, there exists a trade-off between loss in precision and ease in computation [28].

The fuzzy set theory appears as an important tool to provide a multi-objective decision framework that incorporates the vagueness and imprecision inherent in the justification and selection of facility location. Using linguistic variables or fuzzy numbers is an effective way to express objectives including availability of labor, transportation facilities, utilities which can neither be assessed by crisp values nor random processes.

4. Establishing of multi-objective decision model

4.1. Objective evaluation matrix

As stated earlier, the facility location selection problem is a multi-objective decision problem. Thus, the suggested model in this paper consists of n objectives, objective set $\mathbf{B} = \{B_1, B_2, \ldots, B_n\}$, and alternative set (locations) $\mathbf{S} = \{S_1, S_2, \ldots, S_m\}$, from which an optimum location will be selected. One alternative facility location site S_i (i = 1,2,..., m) will be the candidate facility location site that fulfills the predefined objectives. Each alternative facility location site S_i has an evaluation value a_{ij} (or fuzzy language description) under objective B_j (j = 1,2,..., n), then the decision problem will be the choice of an optimum alternative from $S_1, S_2, \ldots, S_m$. The general model, objective evaluation matrix, can be represented as shown in eq. (1);

$$\begin{array}{c} \\ \mathbf{S} = \begin{array}{c} S_1 \\ \vdots \\ S_m \end{array} \end{array} \begin{array}{c} B_1, \quad \cdots \quad, B_n \\ \begin{bmatrix} a_{11}, & \cdots & ,a_{1n} \\ \vdots & & \vdots \\ a_{m1} & \cdots & ,a_{mn} \end{bmatrix} \end{array} = (a_{ij})_{m \times n} . \qquad (1)$$

The process of selection an optimum location, involves mainly two types of objectives. The first type, is the objectives which can be evaluated quantitatively, such as labor or transportation costs. While the other type of objectives such as labor or transportation availability, can be evaluated qualitatively by using 'high', 'low'. For the qualitative type objectives a fuzzy membership degree will be used to convert them into quantitative (fuzzification) value, as described later in section 4.1.2.

In the general model shown in eq. (1) the objective may be quantitative and/or qualitative. In order to be able to deal with these two aspects, a normalization (conversion) process takes place, as demonstrated in the following sections.

4.1.1. Quantitative objective evaluation

Quantitative objectives can be categorized either as benefit or cost, fixed or interval. A set of $\mathbf{O} = \{O_1, O_2, O_3, O_4\}$ will be considered to represent the four types of quantitative objectives. The O_1, O_2, O_3, O_4 represent the objectives as fixed benefit, fixed cost, and interval benefit, and interval cost, respectively. In order to normalize their evaluation value let a_{ij} (i = 1,2,..., m; j = 1,2,..., n) and the following conversion is carried out;

For the fixed benefit (O₁);

$$r_{ij} = \frac{a_{ij} - a_{\min j}}{a_{\max j} - a_{\min j}} \qquad j \in O_1, \qquad (2)$$

where,

$$a_{\max j} = \max_{1 \le i \le m} \{a_{ij}\}, j \in O_1 .$$

For the fixed cost (O₂);

$$r_{ij} = \frac{a_{\max j} - a_{ij}}{a_{\max j} - a_{\min j}} \qquad j \in O_2, \qquad (3)$$

where,

$$a_{\max j} = \max_{1 \le i \le m} \{a_{ij}\}, j \in O_2 .$$

For the interval benefit (O₃);

$$r_{ij} = \begin{cases} 1, a_{ij} = a_j^* \\ 1 - \dfrac{|a_{ij} - a_j^*|}{\Delta_j} \end{cases} \qquad j \in O_3, \qquad (4)$$

where,

$$\Delta_j = \max_{1 \le i \le m} | a_{ij} - a_{ij}^* |, j \in O_3 ,$$

a_j^* Given fixed value (optimum value) of objective j

For the interval cost (O₄);

$$r_{ij} = \begin{cases} 1 - \dfrac{d_j^1 - a_{ij}}{\delta_j} & a_{ij} < d_j^1 \\ 1, a_{ij} \in \left[d_j^1, d_j^2\right] & \\ -1 - \dfrac{a_{ij} - d_j^2}{\delta_j} & a_{ij} > d_j^2 \end{cases} \qquad j \in O_4, \qquad (5)$$

where:

d_j^1 is the Lower limited value of interval of objective j,

d_j^2 is the Upper limited value of interval of objective j, and

$\delta_j = \max\{d_j^1 - a_{\min j}, a_{\max j} - d_j^2\}, j \in O_4$.

4.1.2. Qualitative objective evaluation

Qualitative objective can only be evaluated using linguistic variable (fuzzy language) such as 'high', 'medium', 'low'. An efficient way to deal with this data is the fuzzy set theory, as explained in section 3. Membership functions are used to convert evaluation language into quantitative value, see fig. 1. For that purpose, three scales of evaluation were selected: 1, 0.5, 0.25 which denotes "high" or "good", "medium" or "adequate" and "low" or "poor", respectively.

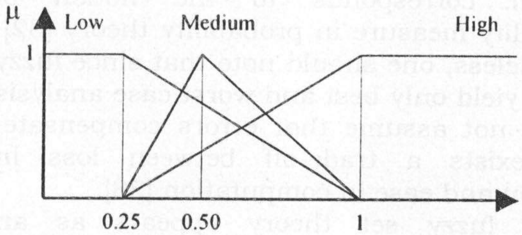

Fig. 1. Membership function.

4.1.3. Normalized evaluation matrix

By integrating the two conditions of quantitative and qualitative evaluating, the standardized (normalized) comprehensive evaluating matrix can be deduced as shown in eq (6);

$$\mathbf{R} = \begin{array}{c} \\ S_1 \\ \vdots \\ S_m \end{array} \begin{array}{c} B_1, \quad \cdots \quad , B_n \\ \begin{bmatrix} r_{11}, & \cdots & , r_{1n} \\ \vdots & & \vdots \\ r_{m1} & \cdots & , r_{mn} \end{bmatrix} \end{array} = (r_{ij})_{m \times n}, \qquad (6)$$

where $0 \le r_{ij} \le 1$.

4.2. Evaluation of facility location site alternatives

4.2.1. Schemes of partiality (preference) information

In practice, there are many occasions where decision-makers have their preference towards certain alternatives. And in order to make the fuzzy model a practical tool, preferences should be taken into consideration.

Suppose that two facility location sites S_i and S_k, the partiality (preference) of one over the other is denoted by η_{ik}, and the preference information evaluation method is conducted as follows:

1) If location S_i has identical preference as S_k, then $\eta_{ik} = \eta_{ki} = 4$.
2) If location S_i has slight preference than S_k, then $\eta_{ik} = 4 + 1, \eta_{ki} = 4 - 1$.
3) If location S_i has evident preference than S_k, then $\eta_{ik} = 4 + 2, \eta_{ki} = 4 - 2$.
4) If location S_i has much more preference than S_k, then $\eta_{ik} = 4 + 3, \eta_{ki} = 4 - 3$.
5) If location S_i has extreme preference than S_k, then $\eta_{ik} = 4 + 4, \eta_{ki} = 4 - 4$.

Let, $$t_i = \sum_{k}^{m} \eta_{ik}, (i = 1,2,\cdots,m). \qquad (7)$$

Then, for every S_i, partiality degree p_i can be calculated, as shown in eq. (8).

$$p_i = t_i / \sum_{k=1}^{m} t_k. \qquad (8)$$

4.2.2. Ranking score for facility location site alternatives

From the normalized evaluating matrix eq (6), each facility location site can be evaluated and a ranking score can be calculated. Next are the procedures to be followed to calculate the ranking score:

Let, $r_j^+ = \max_{1 \le i \le m} \{r_{ij}\}$, $r_j^- = \min_{1 \le i \le m} \{r_{ij}\}$ and,

$$S^+ = (r_1^+, r_2^+, \cdots, r_n^+), \quad S^- = (r_1^-, r_2^-, \cdots, r_n^-).$$

Then, the distance of each facility location site alternative to S^+ and S^- can be determined as follows, eqs. (9) and (10);

$$d_i^+ = d(S_i, S^+)[\sum_{j=1}^{n} (w_j r_{ij} - w_j r_j^+)^2]^{1/2} (i = 1,2,\cdots,m), \qquad (9)$$

$$d_i^- = d(S_i, S^-)[\sum_{j=1}^{n} (w_j r_{ij} - w_j r_j^-)^2]^{1/2} (i = 1,2,\cdots,m), \qquad (10)$$

where w_j is the weight of objective j, for which,

$$\sum_{j=1}^{n} w_j = 1.$$

To calculate the ranking score λ_i for each facility location site;

Let, $d^+ = \min_{1 \le i \le m} \{d_j^+\}$, $d^- = \max_{1 \le i \le m} \{d_j^-\}$ for each objective (B), and

$$C_i = d_i^+ / d^+ - d_i^- / d^-. \qquad (11)$$

From eqs. (8) and (11);

$$\lambda_i = C_i(1 - p_i) \qquad (i = 1,2,\cdots,m). \qquad (12)$$

Then, $\lambda_i (i = 1,2,\ldots,m)$ can be arranged in the ascending order, the facility location site which has $\lambda_k = \min\{\lambda\}$ is the optimum allocation site.

5. Model application – an illustrative example

In this section, the applicability of the fuzzy multi-objective decision-making procedure as presented in Section 4, is demonstrated through the following illustrative numerical example. In this example, four hypothetical facility locations are considered.

1. Objective construction: Numerous objectives can be considered as important criteria for the facility location site selection. These objectives can have either a quantitative or qualitative nature. Since the main objective of the hypothetical-data example is to validate the suggested model, a single level hierarchy of location objectives including 15 objectives, was constructed, see fig 2.

2. Objective evaluating matrix: Establishing a category of facility location objectives is not generally regarded as a difficult task. Location objectives can be classified as benefit or cost, fixed or interval. For simplicity, objectives are classified only as either fixed benefit or fixed cost.

Besides the issue of categorization, the related, and much more important is the problem of objective quantifiability (evaluation value). Objective quantifiability, for each facility location site requires knowledge and awareness of facility location site characteristics. Table 1 shows the designated evaluation value/level for the objectives of each facility location site.

3. Objective weight allocation: There are many methods to determine the weight of each objective in a multi-objective model, such as Delphi method, AHP method, subjective and objective comprehensive method, entropy method, etc. In this work, Delphi method was used to determine an overall weight of each objective. Table 1 shows the allocated weight of each objective.

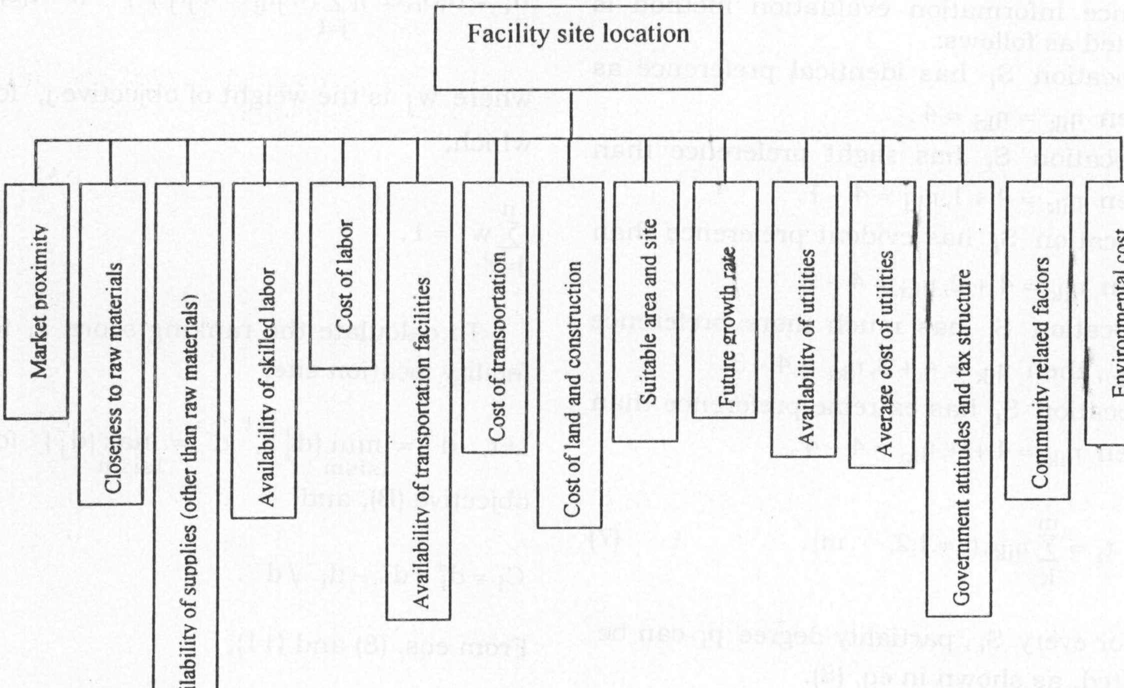

Fig. 2. Hierarchy of location objectives.

Table 1
Evaluation value/level of objectives for facility location sites as well as its overall comprehensive weight

Facility location site objective	Weight (w)	Site (S1)	Site (S2)	Site (S3)	Site (S4)
Market proximity (km) **	0.11	220	170	30	110
Closeness to raw materials (km) **	0.11	8	45	165	5
Availability of supplies (other than raw materials) *	0.09	Medium	Medium	High	Low
Availability of skilled labor level *	0.05	Good	Adequate	Adequate	Poor
Cost of labor ($/hr) **	0.09	0.80	0.85	0.90	0.75
Availability of transportation facilities level *	0.07	Good	Adequate	Adequate	Poor
Cost of transportation ($/day/person) **	0.07	0.25	1.00	0.75	0.75
Cost of land and construction ($/m²) *	0.10	500	250	250	180
Suitable area and site percent *	0.03	60%	90%	85%	75%
Future growth rate *	0.02	Low	High	High	Medium
Availability of utilities level *	0.06	Adequate	Adequate	Adequate	Poor
Average cost of utilities ($/unit production) **	0.07	0.25	0.18	0.18	0.15
Government attitudes and tax structure level **	0.03	Medium	Low	Low	Low
Community related factors level *	0.03	Good	Adequate	Adequate	Poor
Environmental cost ($/year/unit product)**	0.07	18	12	12	8

* Fixed benefit ** Fixed cost

4. Preference information: Preference information is an essential component of the suggested model. A preference matrix includes the decision-makers' preferences for the different facility location sites is constructed as follows:

$$\mathbf{P} = \begin{bmatrix} 4 & 2 & 6 & 7 \\ 6 & 4 & 6 & 2 \\ 2 & 2 & 4 & 6 \\ 1 & 6 & 2 & 4 \end{bmatrix}.$$

By applying eqs. (7) and (8), then the partiality degree for the different facility location sites are:

$$p_1 = 0.296\,,\ p_2 = 0.281\,,\ p_3 = 0.218\,,$$
$$p_4 = 0.203$$

5. Optimum location decision: From table 1, and applying eqs. (2-5) and the fuzzy number quantity conversion model as shown in section 4.1.2, the normalized evaluation matrix of objectives is as follows;

$$\begin{bmatrix} 0 & 0.26 & 1 & 0.57 \\ 0.98 & 0.75 & 0 & 1 \\ 0.50 & 0.50 & 1 & 0.25 \\ 1 & 0.50 & 0.50 & 0.25 \\ 0.67 & 0.33 & 0 & 1 \\ 1 & 0.50 & 0.50 & 0.25 \\ 1 & 0 & 0.33 & 0.33 \\ 0 & 0.78 & 0.78 & 1 \\ 0 & 1 & 0.83 & 0.50 \\ 0.25 & 1 & 1 & 0.50 \\ 0.50 & 0.50 & 0.50 & 0.25 \\ 0 & 0.70 & 0.70 & 1 \\ 0.50 & 1 & 1 & 1 \\ 1 & 0.50 & 0.50 & 0.25 \\ 0 & 0.6 & 0.6 & 1 \end{bmatrix}$$

From the evaluation matrix previously

mentioned the values of S^+ and S^- can be detremined as follows;

$$S^+ = (1,1,1,1,1,1,1,1,1,1,1,1,1,1,1),$$

$$S^- = (0,0,0.25,0.25,0,0.25,0,0,0,0.25, 0.25,0,0.50,0.25,0).$$

The distance of each facility location site alternative can be determined by applying eqs. (9), and (10), see tables 2 and 3.

Table 2
Distance of facility location site alternative to S^+

d_1^+	d_2^+	d_3^+	d_4^+
0.1925	0.1504	0.1640	0.1265

Table 3
Distance of facility location site alternative to S^-

d_1^-	d_2^-	d_3^-	d_4^-
0.1599	0.1461	0.1710	0.2111

From tables 2 and 3, and by applying eq. (11), the values C_i (ranking score without partiality criteria) of each location are as follows:

$$C_1 = 0.764\ ,\ C_2 = 0.497\ ,\ C_3 = 0.482\ ,\ C_4 = 0\ .$$

The ranking score λ_i for each facility location site is calculated by applying equation (12), as shown in table 4.

Table 4
Ranking score λ_i for each facility location site

λ_1	λ_2	λ_3	λ_4
0.5379	0.3573	0.3769	0

From table 4, the order of priority of facility location sites can be concluded as follows: S_4 (first priority - minimum ranking score λ_i), S_2 (second priority), S_3 (third priority) and S_1 (fourth priority), i.e. location S_4 is the optimum location.

This example demonstrates the practicality of the suggested fuzzy multi-objective model. The model is capable to host more facility location sites, as well as more objectives. Moreover, it facilities reaching decisions swiftly and at a reasonable quality. However, it is worth noting that the benefit obtained due to the ease in computation in applying fuzzy decision models may be balanced by a possible loss in precision since fuzzy models provide only best and worst case analysis and do not assume that error compensate.

6. Conclusions

The principal advantage of the fuzzy multi-objective with partiality criteria used in this study is that it provides decision maker with consistent ranking of location alternatives. Hence, consequently they obtain a final ranking for the facility location selection alternatives by taking into account not only the economic criterion, but also the key strategic justification criteria by utilizing linguistic variables.

The decision model presented in this paper can be easily computerized, and allows for assessment of facility location selection taking into consideration excessive criteria set and a large number of alternatives. Further more, the what-if analysis can be performed and generate different scenarios. Combining the model with other decision tools such as AHP will make it possible for decision makers determine the values of weight of each objective systematically.

References

[1] D. Lampert, Site Selection and Investigation - A Practical Handbook, D. Lampert, and D. Woodley, (Editors), Gower Publishing Company limited (1991).

[2] A. Weber, Uber den Standort der Industrien (Alfred Weber's Theory of the Location of Industries), University of Chicago (1929).

[3] C.H. Aikens, Facility Location Models for Distribution Planning, European Journal of Operational Research, Vol. 22, pp. 263-279 (1985).

[4] J. Current; H. Min and D. Schilling, Multiobjective Analysis of Facility Location Decision, European Journal of Operational Research, Vol. 49, pp. 295-307 (1990).
[5] S.H. Owen and M.S. Daskin, Strategic Facility Location: A Review, European Journal of Operational Research, Vol. 111(3), pp. 423-447 (1998).
[6] A.J. Scott, Dynamic Location-Allocation Systems: Some Basic Planning Strategies, Environment and Planning, Vol. 3, pp. 73-82 (1971).
[7] G.O. Wesolowsky, Dynamic Facility Location, Management Science, Vol. 19 (11), pp. 1241-1248 (1973).
[8] D.A. Schilling, Dynamic Location Modeling for Public-Sector Facilities: A Multicriteria Approach, Decision Sciences, Vol. 11, pp. 714-724 (1980).
[9] F.V. Louveaux, Stochastic Location Analysis, Location Science, Vol. 1(2), pp. 127-154 (1993).
[10] M.L. Brandeau and S.S. Chiu, An Overview of Representative Problems in Location Research, Management Science, Vol. 35 (6), pp. 645-674 (1989).
[11] B. Tansel; R. Francis and T. Lowe, Location on Networks: A Survey, Management Science, Vol. 29, pp. 482-492 (1989).
[12] A.J. Scott, Location-allocation Systems: A Review, Geographical Analysis, Vol. 2, pp. 95-119 (1970).
[13] S. Kolli and G.W. Evans, A Multiple Objective Integer Programming Approach for Planning Franchise Expansion, Computers and Industrial Engineering, Vol. 37 (3), pp. 543-561 (1999).
[14] A. Geoffrion, A Guide to Computer Assisted Methods for Distribution System Planning, Sloan Management Review, Vol. 24(5), pp. 535-544 (1978).
[15] S.L. Hakimi and C.C. Kuo, On a General Network Location-Production-Allocation Problem, European Journal of Operational Research, Vol. 55 (1), pp. 31-45 (1991).
[16] R. Amador and S. Starbird, The Evaluation of International Agribusiness Investment Locations Using Multidimensional Scaling, Regional Science and Urban Planning, Vol. 5, pp. 139-151 (1989).
[17] M. Carreras, and D. Serra, On Optimal Location with Threshold Requirements, Socio-economic Planning Sciences, Vol. 33 (2), pp. 91-103 (1999).
[18] C.C. Branas and C.S. Revelle, An Iterative Switching Heuristic to Locate Hospitals and Helicopters, Socio-economic Planning Sciences, Vol. 35 (1), pp. 11-30 (2001).
[19] K.A. Willoughby and D.H. Uyeno, Resolving Splits in Location/Allocation Modeling: A Heuristic Procedure for Transit Center Decisions, Transportation Research Part E: Logistics and Transportation Review, Vol. 37 (1), pp. 71-83 (2001).
[20] W.M. Bowen, A Thurstonian Comparison of the Analytic Hierarchy Process and Probabilistic Multidimensional Scaling through Application to the Nuclear Waste Site Selection Decision, Socio-economic Planning Sciences, Vol. 29 (2), pp. 151-163 (1995).
[21] S. Lee, On Solving Unreliable Planar Location Problems, Computers and Operations Research, Vol. 28(4), pp. 329-344 (2001).
[22] M.T. Marsh, and D.A. Schilling, Equity Measurement in Facility Location Analysis: A Review and Framework, European Journal of Operational Research, Vol. 74(1), pp. 1-17 (1994).
[23] G. Righini, A Double Annealing Algorithm for Discrete Location/Allocation Problems, European Journal of Operational Research, Vol. 86 (3), pp. 452-468 (1995).
[24] S. Lee; G. Green, and C. Kim, A Multiple Criteria Model for the Location-Allocation Problem, Computers and Operations Research, Vol. 8(1), pp. 1-8 (1981).
[25] V. Maniezzo; I. Mendes, and M. Paruccini, Decision Support for Siting problems, Decision Support Systems, Vol. 23 (3), pp. 273-284 (1998).
[26] J. Korpela, and M. Tuominen, A Decision Aid in Warehouse Site Selection, International Journal of Production Economics, Vol. 45(1-3), pp. 169-180 (1996).

[27] R.E. Bellman, and L.A. Zadeh, Decision-Making in a Fuzzy Environment, Management Science, Vol. 17(4), pp. 141-164 (1970).
[28] D. Dubois, and H. Prade, Fuzzy Sets and Statistical Data, European Journal of Operational Research, Vol. 25, pp. 345-356 (1986).
[29] G.J. Klir, and T.A. Folger, Fuzzy Sets, Uncertainty and Information, Prentice-Hall International (1988).
[30] A. Kaufmann, and M.M. Gupta, Mathematical Models in Engineering and Management Science. Elsevier Science Publisher, 2nd ed. (1991).
[31] T.J. Ross, Fuzzy Logic with Engineering Applications, McGraw-Hill (1995).
[32] K. Tanaka, An Introduction to Fuzzy Logic for Practical Applications. Springer-Verlag (1991).

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